



Jet Propulsion Laboratory
California Institute of Technology

NASA Exoplanet Exploration Program

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Jet Propulsion Laboratory

California Institute of Technology

September 12, 2018

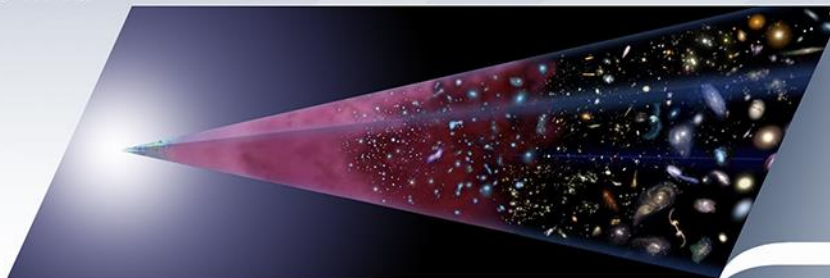
Pasadena, CA

Why Astrophysics?

Astrophysics is humankind's scientific endeavor to understand the universe and our place in it.



How did our universe begin and evolve?



How did galaxies, stars, and planets come to be?



Are we alone?

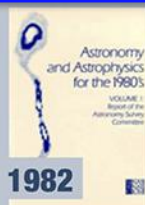


ExEP

Enduring National Strategic Drivers



1972



1982



1991



2001



2010

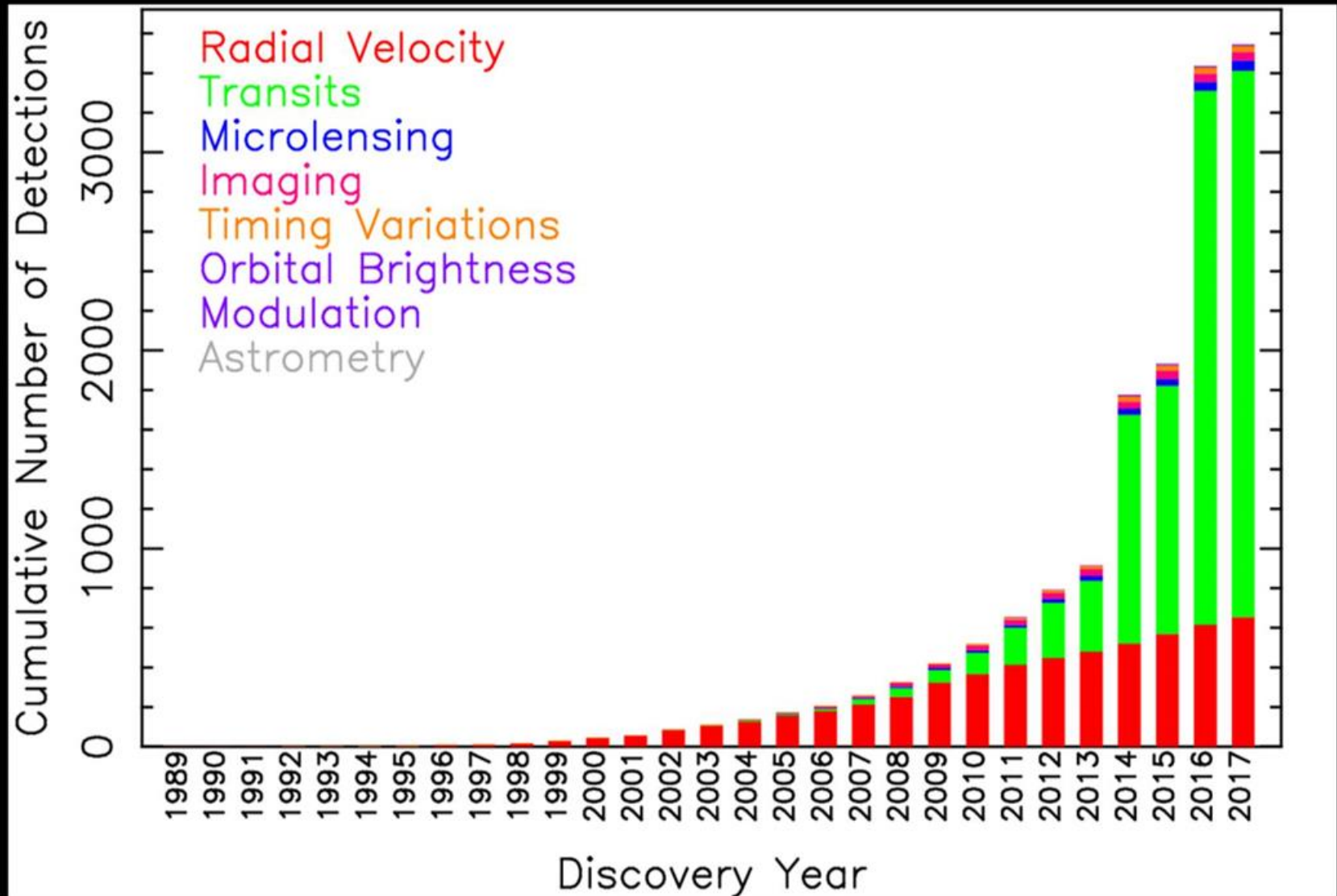
Show Me the Planets! Trappist-1

Seven Exoplanets Above the Fold – 3 in the Habitable Zone



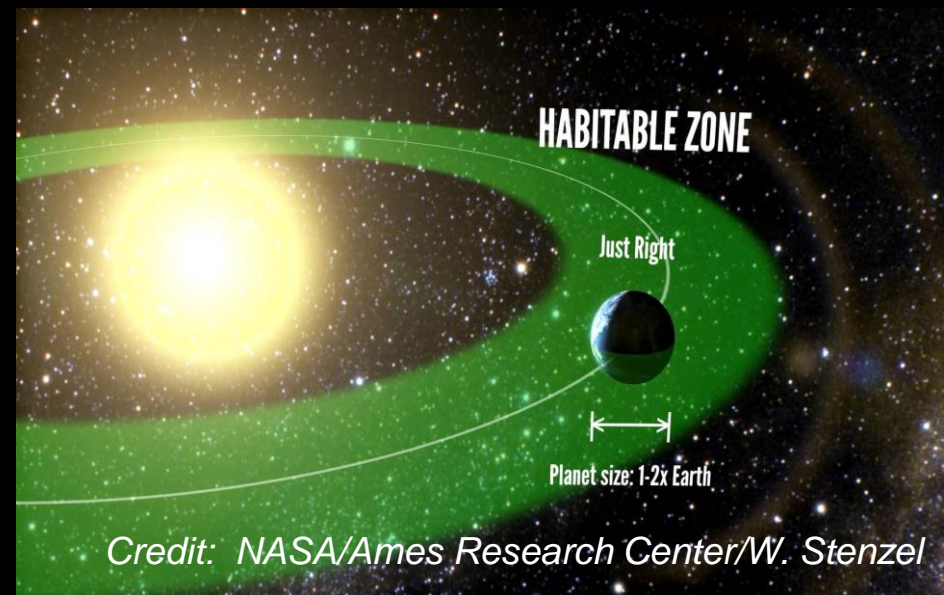
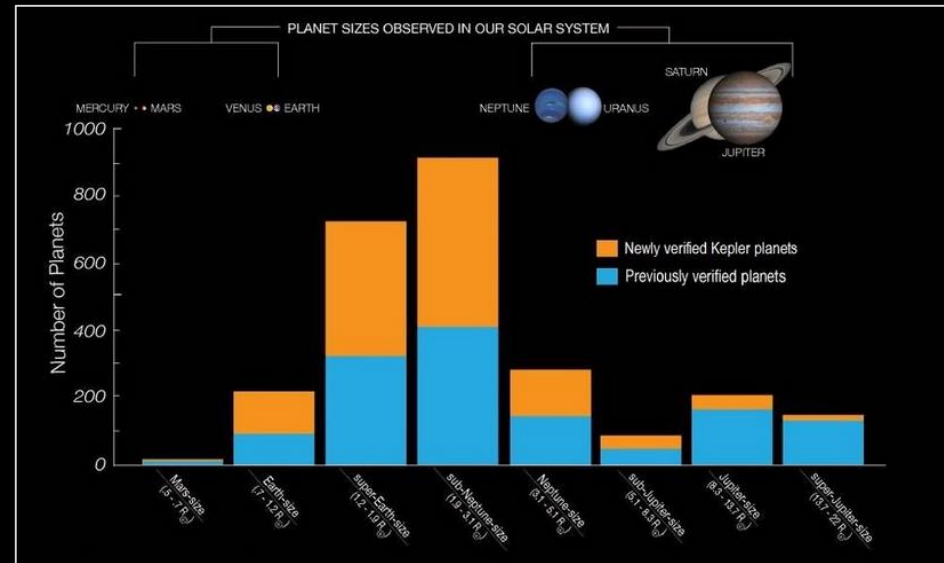
Thousands of Exoplanets

Number doubles every ~26 months. “Mamajek’s Law”



Three Key Kepler Results

1. On average there is at least one planet for each of the stars in the night sky
2. Small planets are the most common type in the Galaxy
3. Earth-sized planets (0.5 to ~1.5 Earth radii) in the Habitable Zone are common



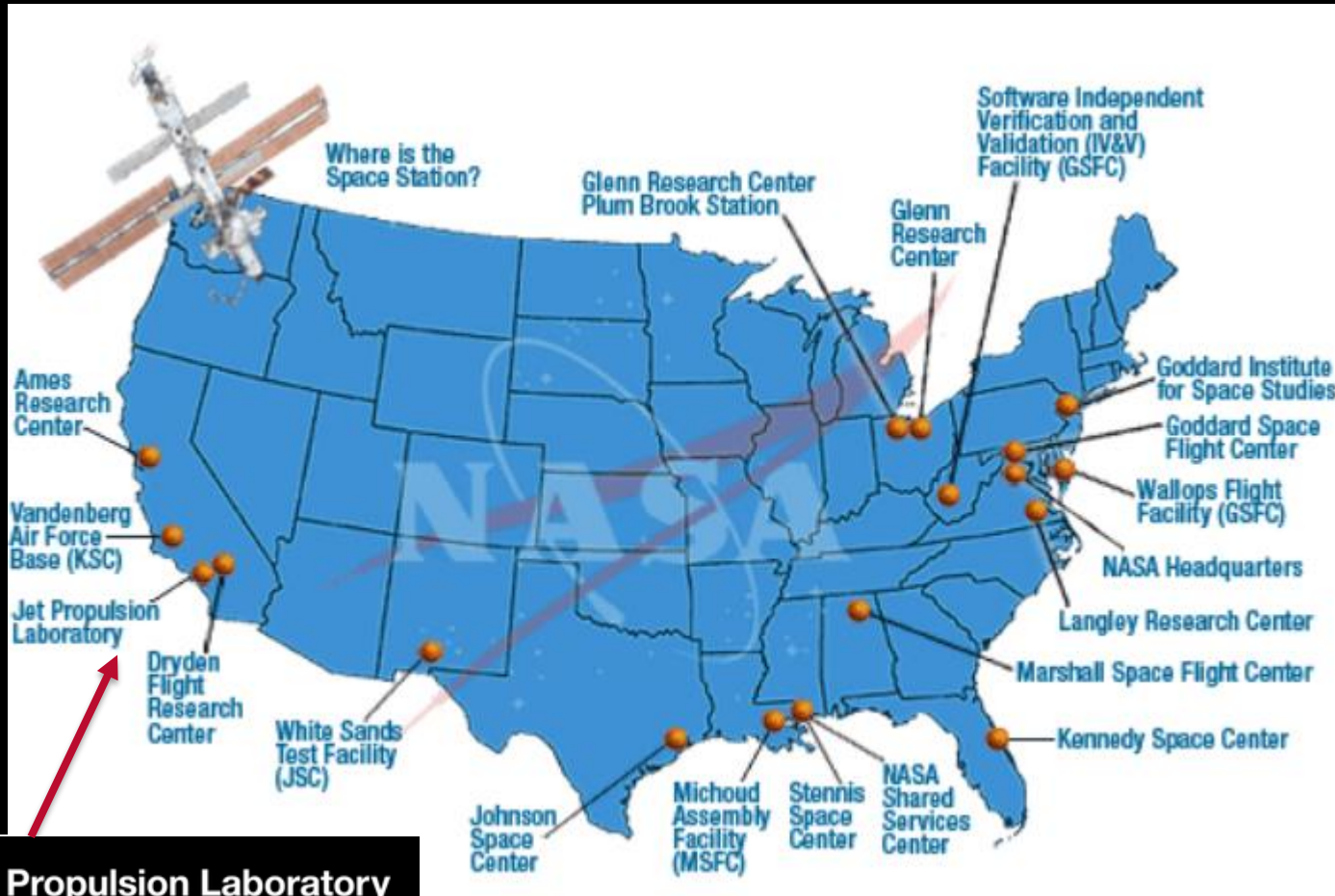
Program Overview

Program Technology

Exoplanet Science Institute

NASA Centers and Facilities

JPL is NASA's Federally-Funded Research and Development Center



NASA Exoplanet Exploration Program

Astrophysics Division, NASA Science Mission Directorate

NASA's search for habitable planets and life beyond our solar system



Program purpose described in 2014 NASA Science Plan

1. Discover planets around other stars
2. Characterize their properties
3. Identify candidates that could harbor life

ExEP serves the science community and NASA by implementing NASA's space science vision for exoplanets

<https://exoplanets.nasa.gov>

Exoplanet Missions

NASA Missions

Hubble¹

Spitzer

Kepler

TESS

JWST²

WFIRST

PLATO

CHEOPS⁴

Gaia

CoRoT³

Starshade
Rendezvous⁵

LUVOIR⁵

HabEx⁵

OST⁵

Non-NASA Missions

W. M. Keck Observatory

Large Binocular
Telescope Interferometer

NN-EXPLORE

Ground Telescopes with NASA participation

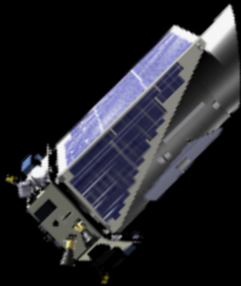
⁵ 2020 Decadal Survey Studies

- ¹ NASA/ESA Partnership
- ² NASA/ESA/CSA Partnership
- ³ CNES/ESA
- ⁴ ESA/Swiss Space Office

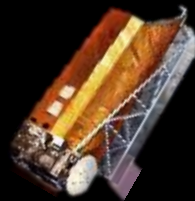
NASA Exoplanet Exploration Program

Space Missions and Mission Studies

K2



Probe-Scale Studies
Starshade Coronagraph



Communications



Supporting Research & Technology

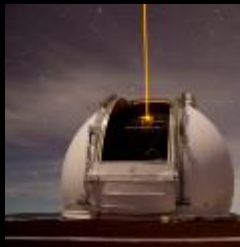
Key Sustaining Research



NN-EXPLORE



Large Binocular
Telescope Interferometer

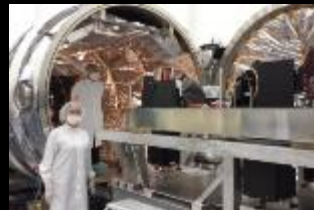


Keck Single
Aperture
Imaging & RV

Occulting Masks



Technology Development Deformable Mirrors



High-Contrast Imaging

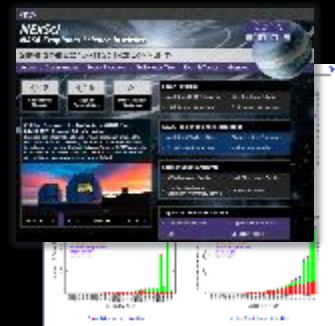


Deployable Starshades

NASA Exoplanet Science Institute



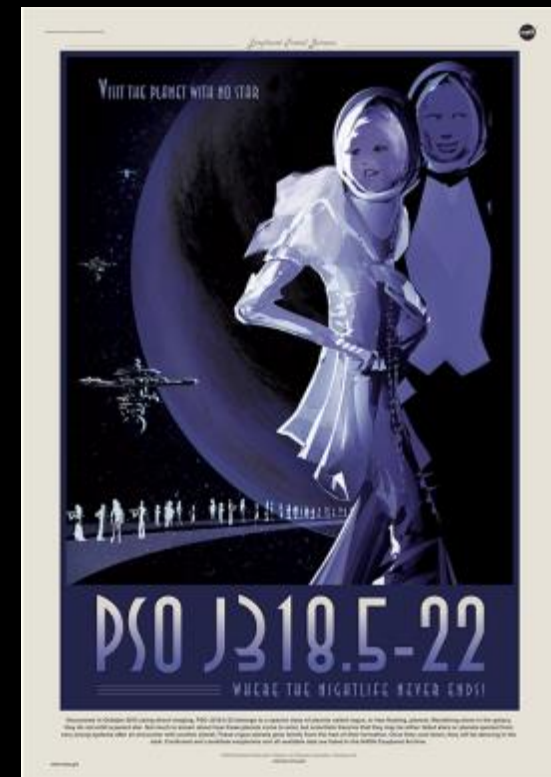
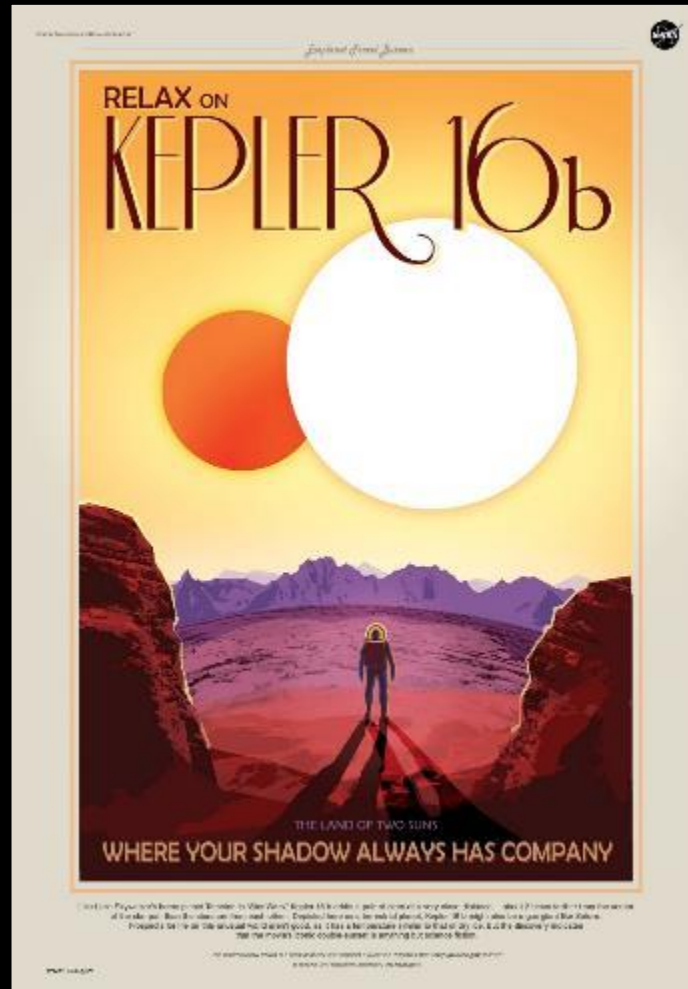
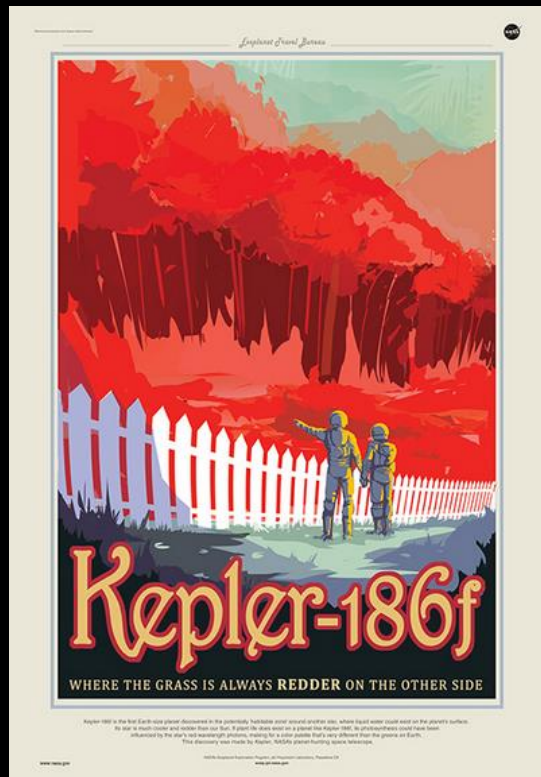
Archives, Tools, Sagan Fellowships,
Professional Engagement



<https://exoplanets.nasa.gov>

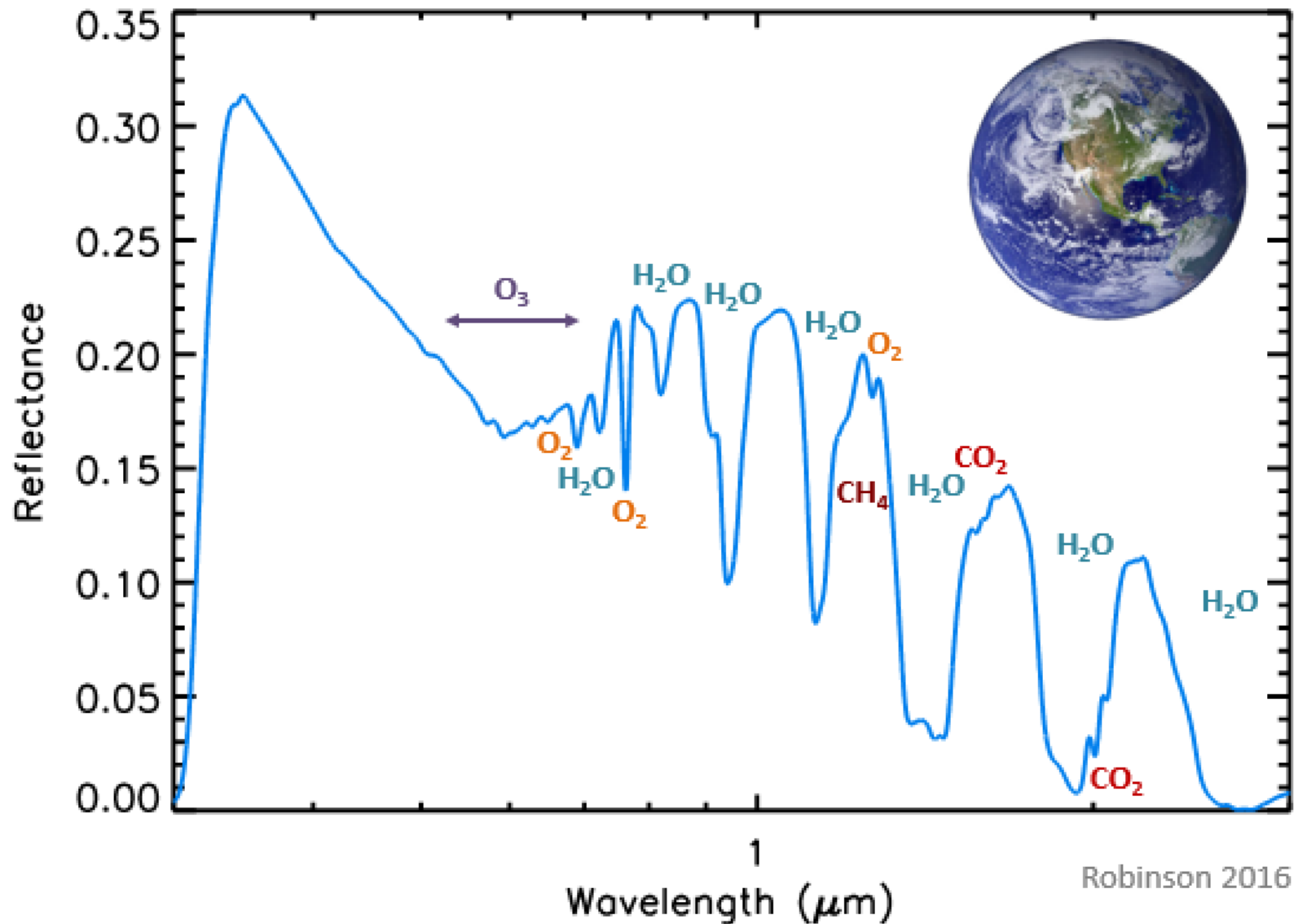
Exoplanet Communications

Explore a Galaxy of Worlds, Inspiring our Own

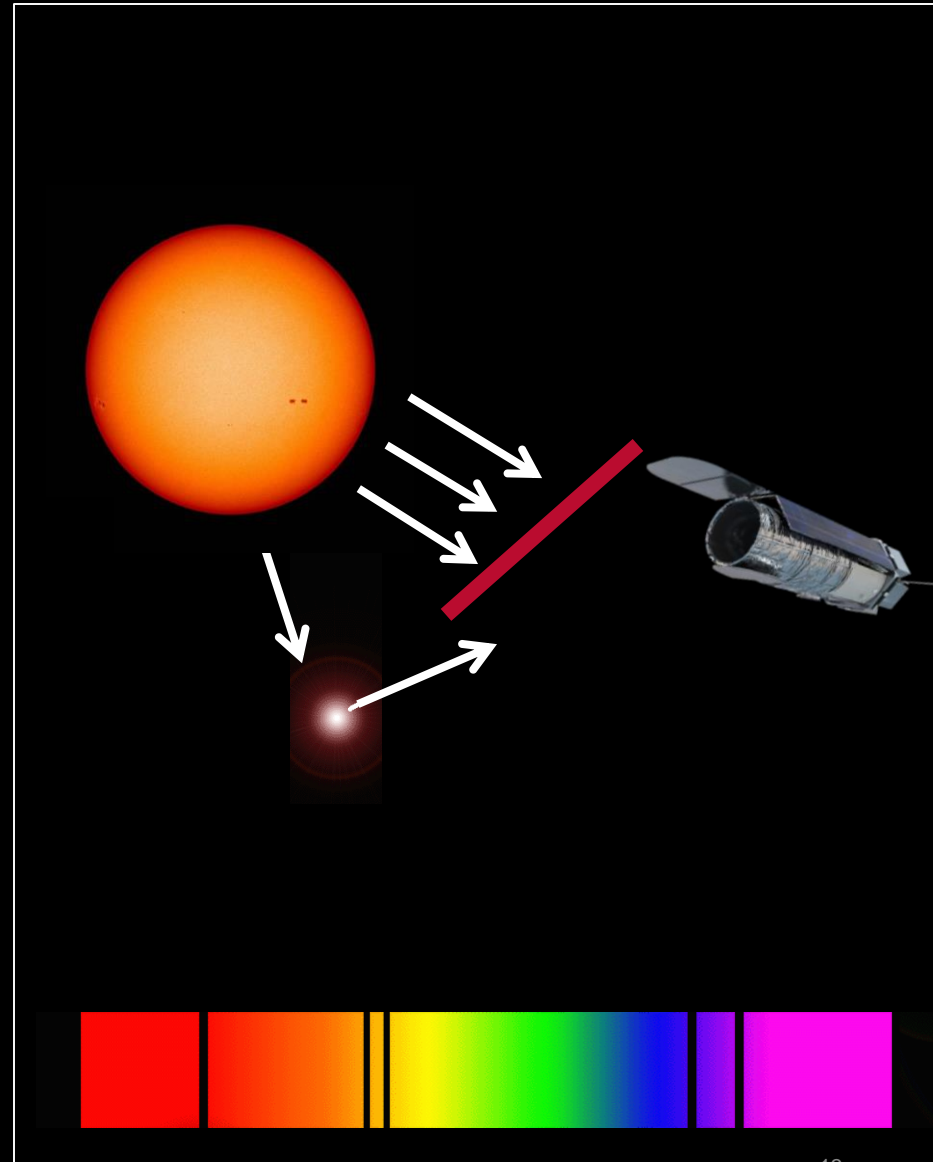


Potential Biosignature Gases

Spectral Lines

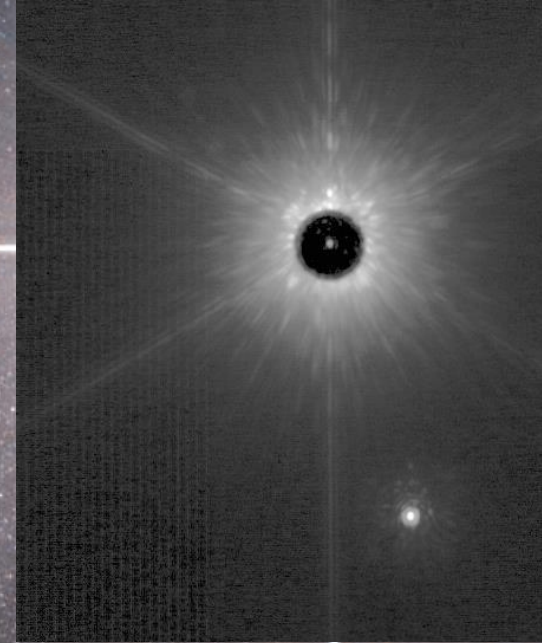
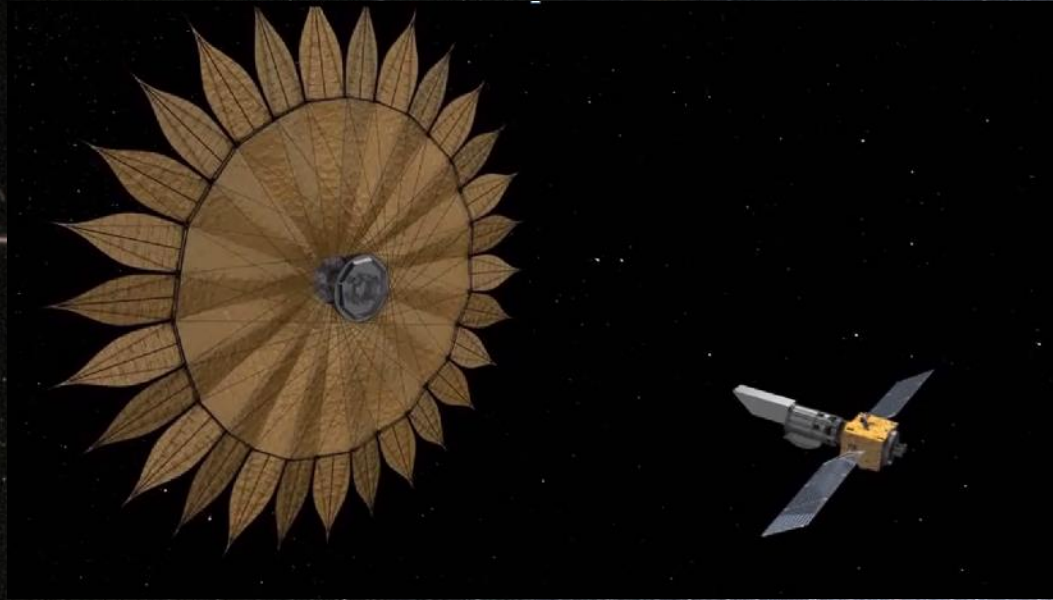


Reflection Spectroscopy

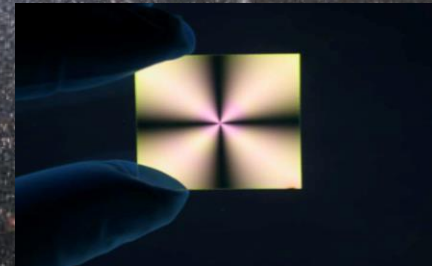


Starlight Suppression is the Key Technology in the Search for Life on Earth-Size Exoplanets

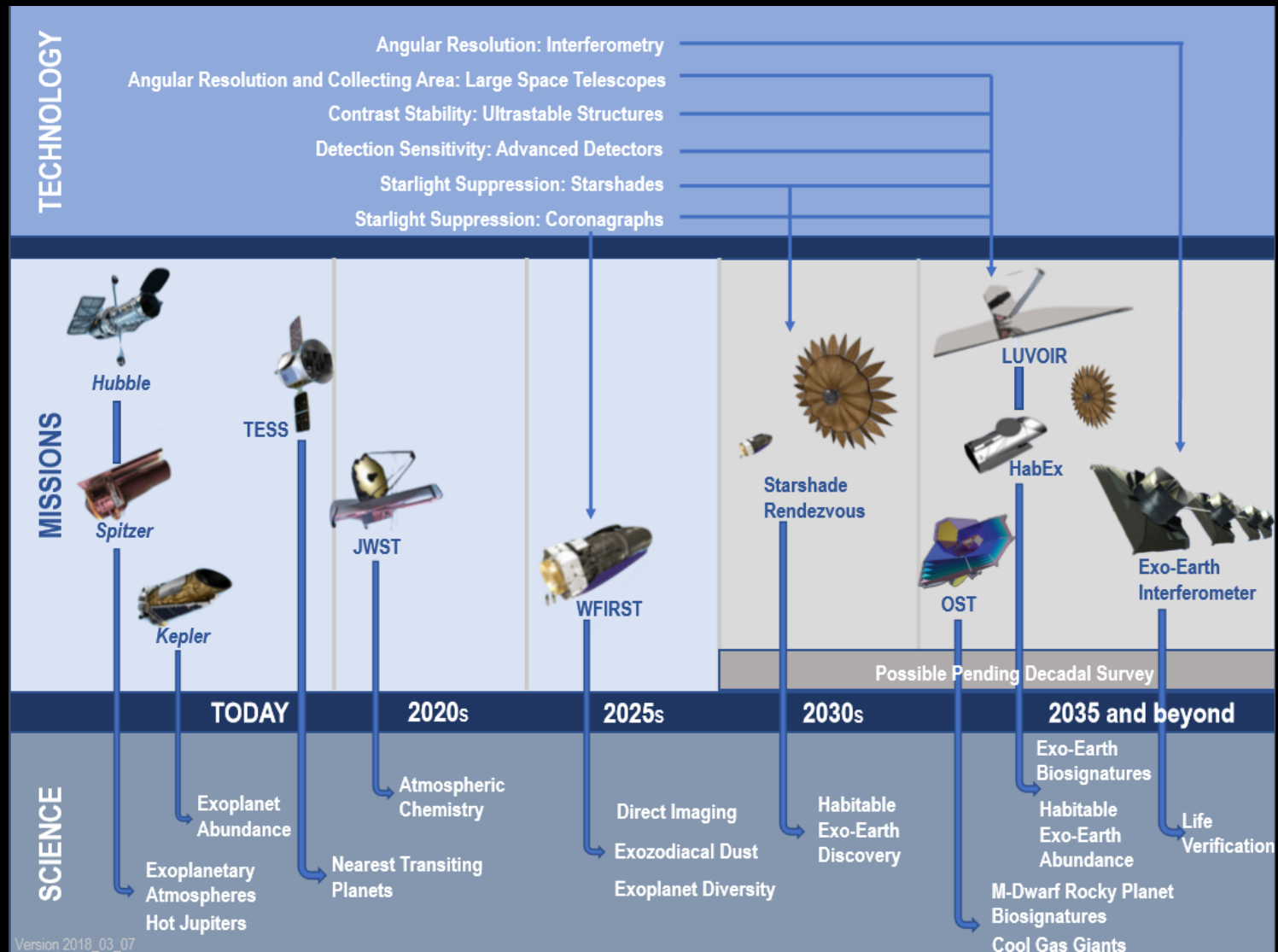
External Occulters (Starshades)



Internal Occulters (Coronagraphs)



ROADMAP OF NASA EXOPLANET MISSIONS, TECHNOLOGY AND SCIENCE



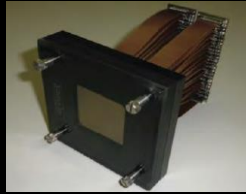


V-NIR Coronagraph/Telescope Technology Gaps

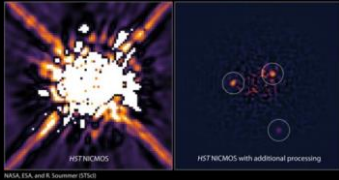
Contrast



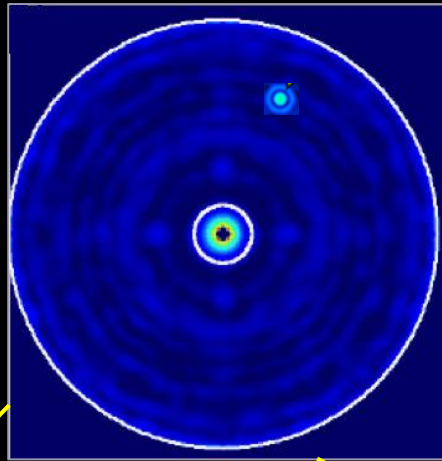
CG-2: Coronagraph Architecture



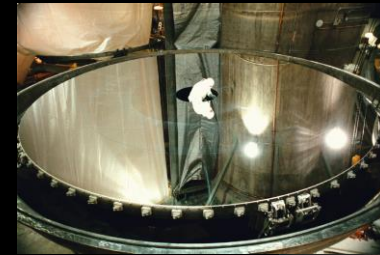
CG-3: Deformable Mirrors



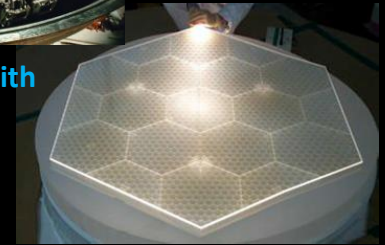
CG-4: Data Post-Processing



Angular Resolution

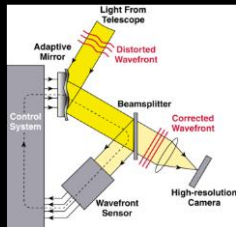


CG-1: Large Monolith Mirrors



CG-1: Segmented Mirrors

Contrast Stability



CG-5: Wavefront Sensing and Control

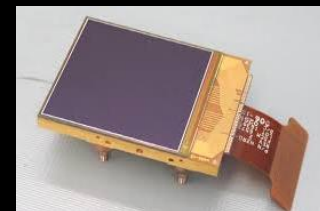
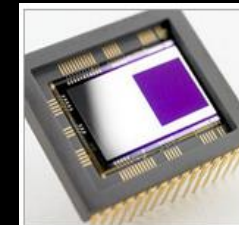


CG-6: Mirror Segment Phasing



CG-7: Telescope Vibration Sensing and Control or Reduction

Detection Sensitivity



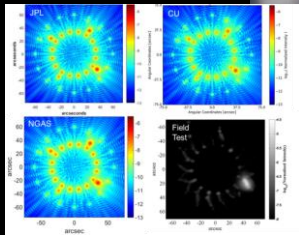
Ultra-low Noise Visible (CG-8) and Infrared (CG-9) Detectors

Starshade Technology Gaps

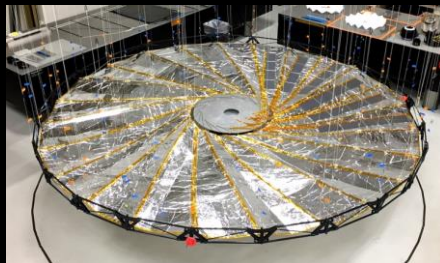
Starlight Suppression



S-1: Controlling Scattered Sunlight



S-2: Starlight Suppression and Model Validation

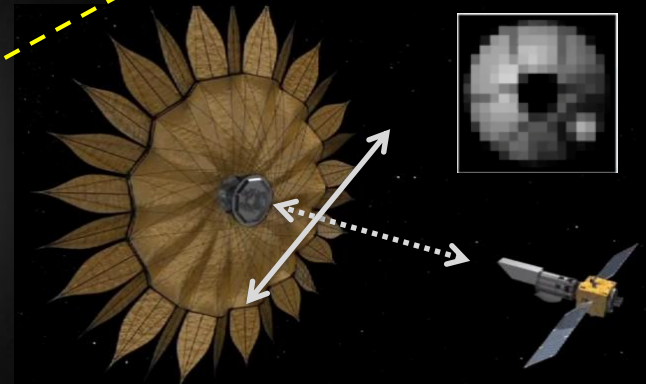


S-5: Petal Positioning Accuracy and Opaque Structure

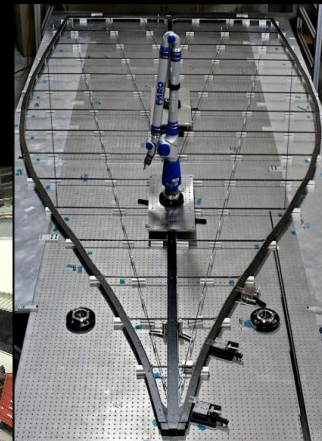
Deployment Accuracy and Shape Stability



Formation Sensing



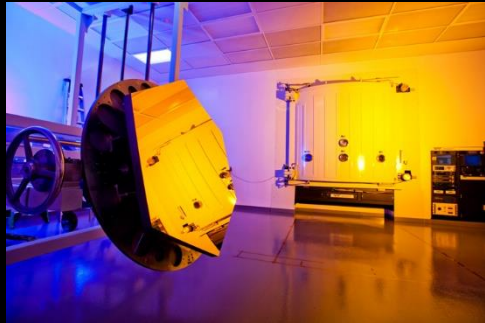
S-3: Lateral Formation Sensing



S-4: Petal Shape And Stability

Other Technology Gaps

UV Contrast

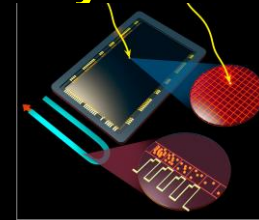


CG-10 UV/V/NIR Mirror Coatings

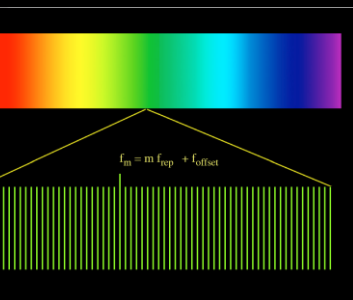
UV Detection Sensitivity



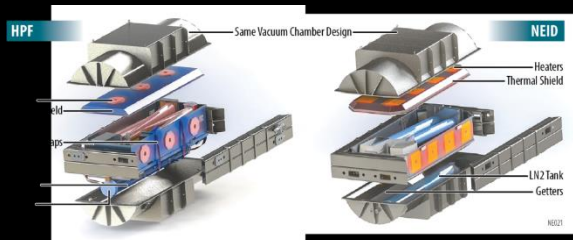
CG-12: Ultra-low Noise UV Detectors



Stellar Reflex Motion Sensitivity

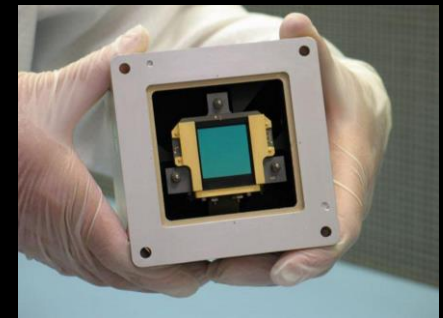


2: Laser Frequency Combs for Space-based EPRV

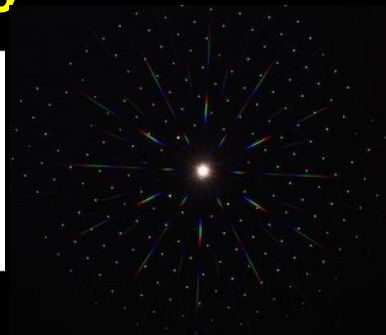


M-1: Ground-based Ultra-high Precision Radial Velocity

Transit Spectroscopy Sensitivity



M-4: Ultra-stable Mid-IR Detectors for Transit Spectroscopy



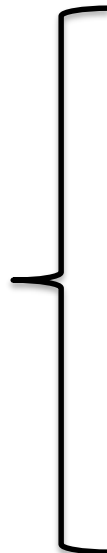
M-3: Astrometry

2018 ExEP Prioritized Technology List



Exoplanet Exploration Program

**Coronagraphs
and
Starshades**



Tech. ID	Technology Title	Impact	Urgency	Trend	2018 Score	2017 Score
	weight:	10	10	5		
CG-2	Coronagraph Architecture	4	4	2	90	85
S-2	Starlight Suppression and Model Validation	4	4	2	90	90
S-1	Controlling Scattered Sunlight	4	4	2	90	90
S-3	Lateral Formation Sensing	4	4	2	90	90
S-5	Petal Positioning Accuracy and Opaque Structure	4	4	2	90	90
S-4	Petal Shape and Stability	4	4	2	90	90
CG-3	Deformable Mirrors	4	4	2	90	80
CG-1	Large Aperture Primary Mirrors	4	3	3	85	85
CG-6	Mirror Segment Phasing	4	3	3	85	85
CG-7	Telescope Vibration Sense/Control or Reduction	4	3	3	85	85
CG-9	Ultra-Low Noise Near-Infrared Detectors	4	3	3	85	85
CG-5	Wavefront Sensing and Control	4	3	2	80	80
CG-8	Ultra-Low Noise Visible Detectors	4	3	2	80	80
M-4	Ultra-Stable Mid-IR detector	3	3	4	80	
M-3	Astrometry	3	3	3	75	
CG-4	Data Post-Processing Algorithms and Techniques	4	2	2	70	70
CG-10	Mirror Coatings for UV/NIR/Vis	3	3	2	70	70
M-2	Space-based Laser Frequency Combs	3	3	2	70	
CG-13	Ultra Low-noise Mid-IR detectors	2	3	4	70	
M-1	Extreme Precision Ground-based Radial Velocity	2	3	3	65	75
CG-14	Mid-IR Large Aperture Telescopes	2	3	3	65	
CG-15	Mid-IR Coronagraph Optics and Architecture	2	3	3	65	
CG-16	Cryogenic Deformable mirror	2	3	3	65	
CG-12	Ultra-Low Noise UV Detectors	2	3	2	60	60



**Mass measurement
to be advanced?**



**Mid-IR interferometry
technology next
decade?**

NASA Exoplanet Science Institute

California Institute of Technology

ipac

NExSci

NASA Exoplanet Science Institute

SERVING THE EXOPLANET SCIENCE COMMUNITY

ABOUT | CONFERENCES | SAGAN PROGRAM | NASA KECK TIME | DATA & TOOLS | MISSIONS

3,509 Confirmed Planets | 4,496 Kepler Candidates | 584 Multi-Planet Systems

Sagan Program

- Apply for a NHFP Fellowship
- Meet the Sagan Fellows
- 2017 Summer Workshop
- Past Summer Workshops

NASA Time on the Keck Telescopes

- Apply for NASA Keck Time
- About the Keck Telescopes
- Keck Observatory Archive
- Keck Instrumentation

Exoplanet Data Archives

- NASA Exoplanet Archive
- Keck Observatory Archive
- Exoplanet Follow-up Observing Program (ExoFOP)
- LBTI Data Archive

Supported Events & Missions

- Exoplanet Exploration
- Supported Conference
- LBTI
- Science at NExSci

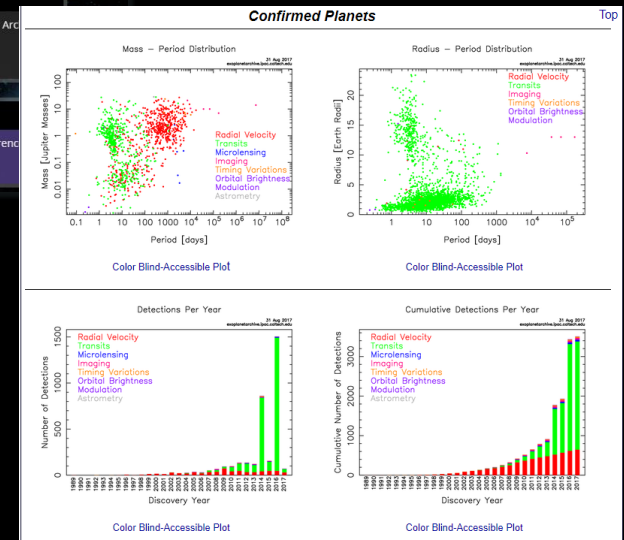
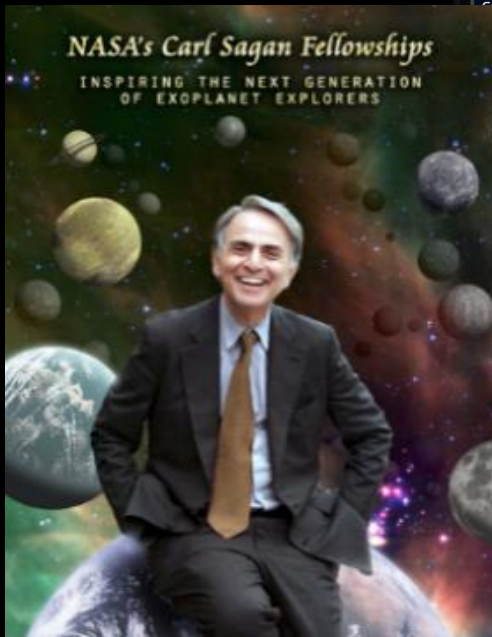
Call for Proposals for NASA Keck 2018A Time

26 July 2017 • Proposal Call Information

Proposal call information to use NASA's portion of time on the Keck telescopes for observing semester 2018A is now available, including a call for Key Strategic Mission Support (KSMS) projects which begin with the 2018A semester. General Mission Support and General Observing proposals are also solicited.

Plots → 1 2 3 4

Exoplanet Archive
Education & Training
Follow-up Observing



Exoplanet Research as a Private-Public Partnership

C. Beichman

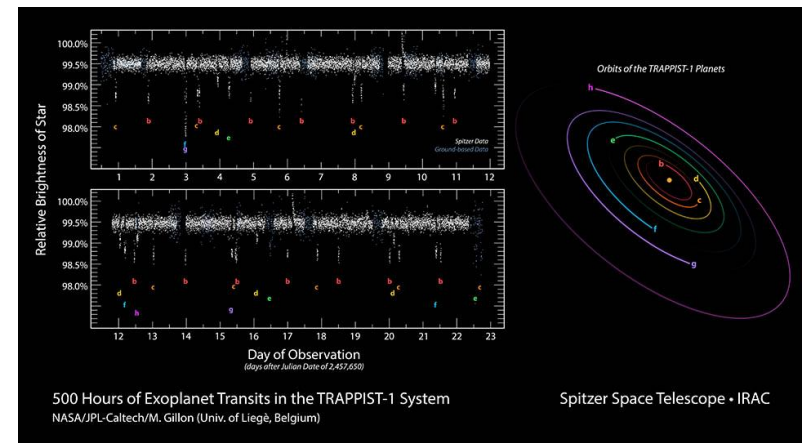
NASA Exoplanet Science Institute

JPL and Caltech

12 September 2018

Are We Alone?

- Exoplanet research and astrobiology draw on astrophysics, solar physics, solar system science, geology and atmospheric science, fundamental biology, and research into life in extreme environments → with the goal of understanding the origins of life, the formation and evolution of habitable worlds, and the breadth of habitable environments and of life itself throughout the Universe
 - The breadth of the topic and its fundamental nature draw both scientists and the general public in a way few other topics in science can
-
- *Seven transiting planets orbiting TRAPPIST-1, a cool star just 39 light years away, were discovered using a small ground based telescope*
 - *Follow-up by the Spitzer Space Telescope and the Hubble Space Telescope showed three are Earth-sized worlds in the Habitable (Goldilocks) Zone*
 - *Announcement attracted over 1 BILLION hits on social media*



Exoplanet Research Built on Federal and Private Funding

- NASA and NSF make large scale investments (hundreds of millions up to billions) impossible for smaller entities, e.g. Hubble, Spitzer, TESS and JWST
- Large scale philanthropic funding (tens to hundreds of millions) has a long tradition in astronomy and is currently benefitting exoplanet research
 - Palomar 200" telescope supported by the Carnegie Foundation (\$6M in 1928)
 - Twin Keck Telescopes developed with funds from Keck foundation & NASA (1/6 share)
 - The Thirty Meter Telescope initiated with a major gift from the Moore Foundation
- On a slightly smaller scale (hundreds of thousands to a few millions) the Moore, Heising-Simons and Templeton Foundations support instrumentation at many institutions including exoplanet science at Keck and Palomar
- The Simons Foundation supports 8-10 postdoctoral fellowships per year (51 Peg program) at elite universities in addition to more broadly based national fellowship programs such as NASA's Sagan Fellowships, NASA Fellowships, etc

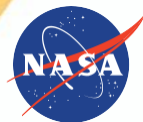
Numerous Opportunities for Philanthropic Support Of Exoplanet Science

- Illustrative Instrumentation Concept (there are many more)
 - Keck Planet Finder is a Caltech/Keck Observatory initiative to develop a state-of the-art Precision Radial Velocity (PRV) instrument
 - Validate and determine masses and orbits of the most compelling exoplanet candidates from Kepler, TESS in preparation for observation by JWST
 - Identify small planets suitable for direct imaging by future large ground-based telescopes and space telescopes
 - **Open to the whole exoplanet community via NASA access to Keck**
 - PRV received endorsement by recent National Academy review of exoplanet strategy
- People
 - Exoplanet science has a long time horizon and bringing in young scientists is critical
 - Support for undergraduates, graduate students and, to a lesser extent, postdocs can make a big difference to progress in exoplanet science



Jet Propulsion Laboratory
California Institute of Technology

Break for Lab Tour



Jet Propulsion Laboratory
California Institute of Technology

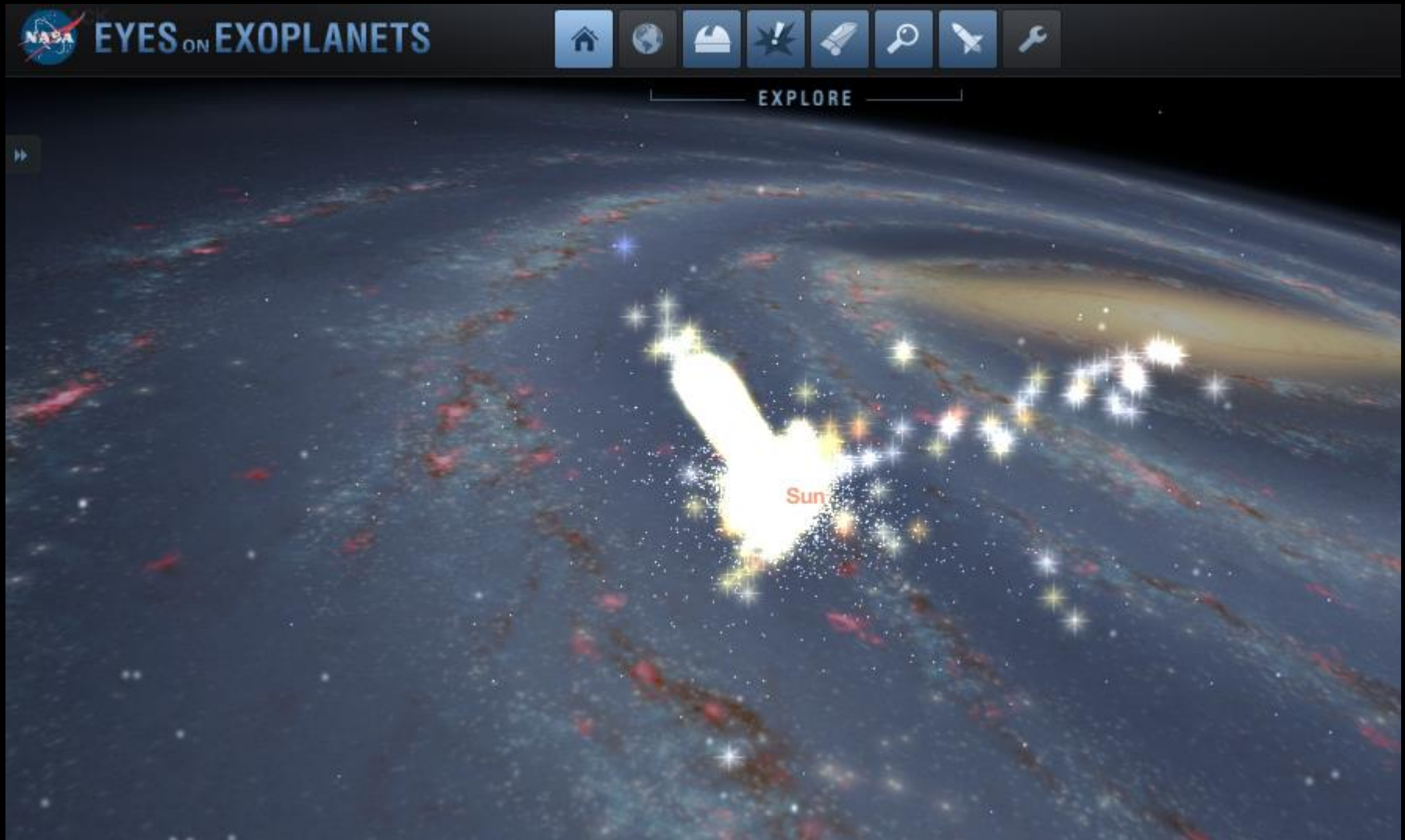
Welcome to the Starshade Lab!

NASA Exoplanet Exploration Program

CL#17-3226

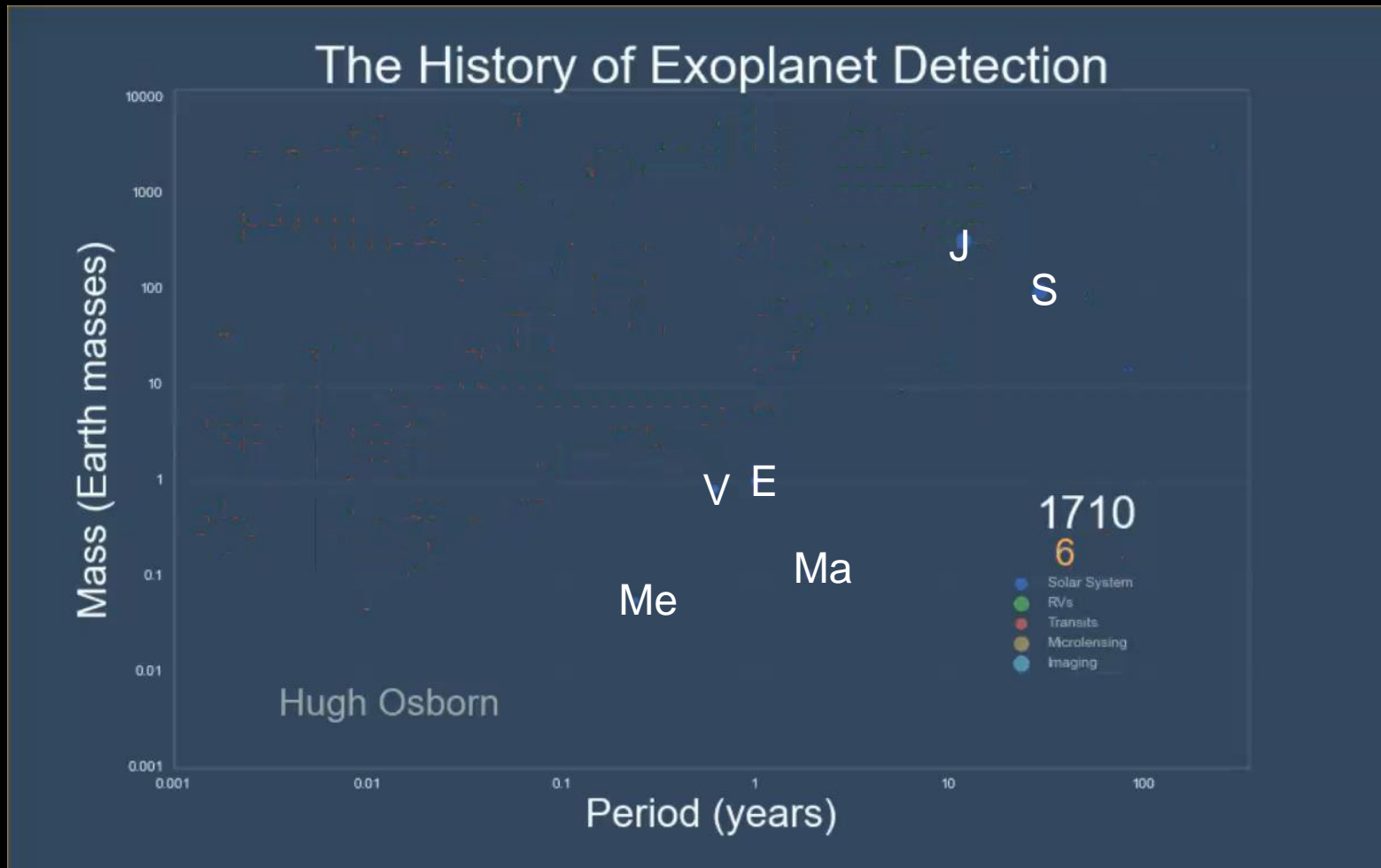
Where are the Exoplanets?

Visualization from *Eyes on Exoplanets*



Show Me the Planets!

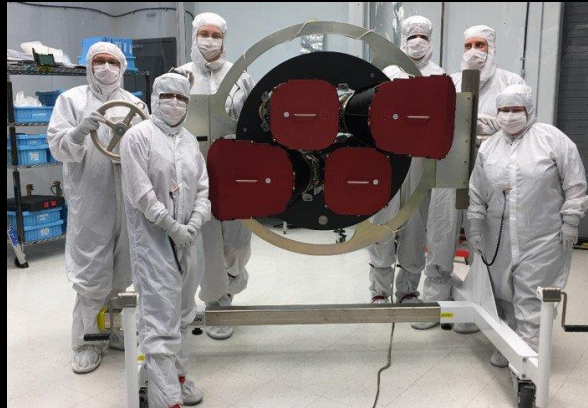
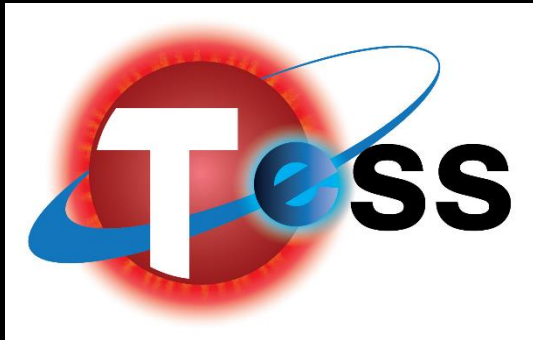
Mass vs Orbital Period



Credit: Hugh Osborn

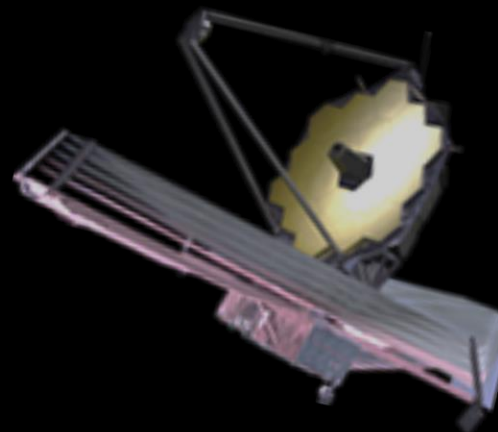
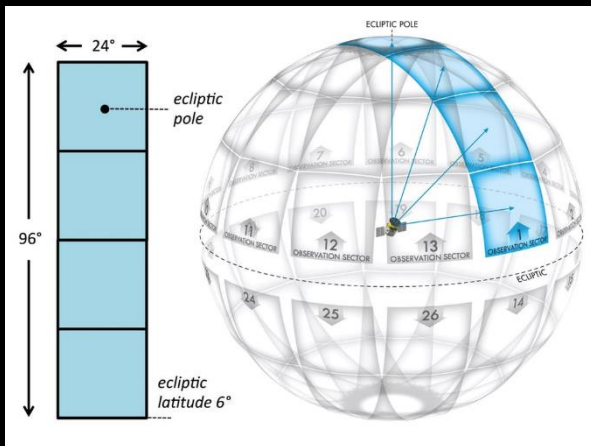
Transiting Exoplanet Survey Satellite

Provides targets for James Webb Space Telescope



- Designed to find transiting planets around nearby stars
- Will survey the entire sky
- Order of magnitude more planets than Kepler

Provides targets for JWST transit spectroscopy

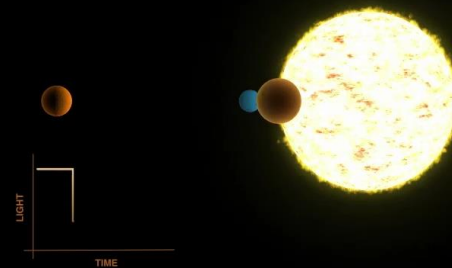


How Do We Find Exoplanets?

Two Popular Methods



Doppler Spectroscopy
(Radial Velocity)



Transit

Transmission Spectroscopy

Sunny with a Chance of Clouds

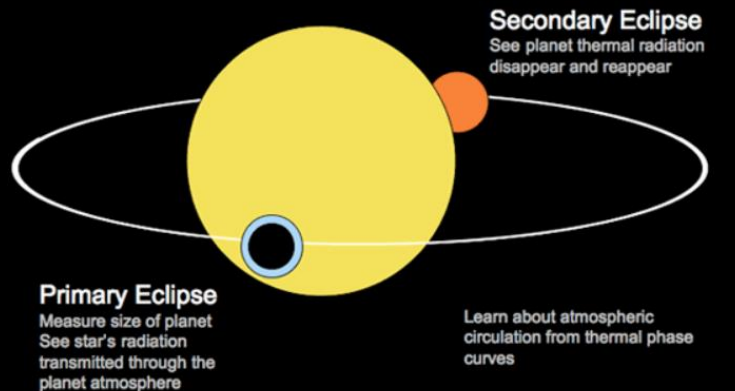


Figure by S. Seager

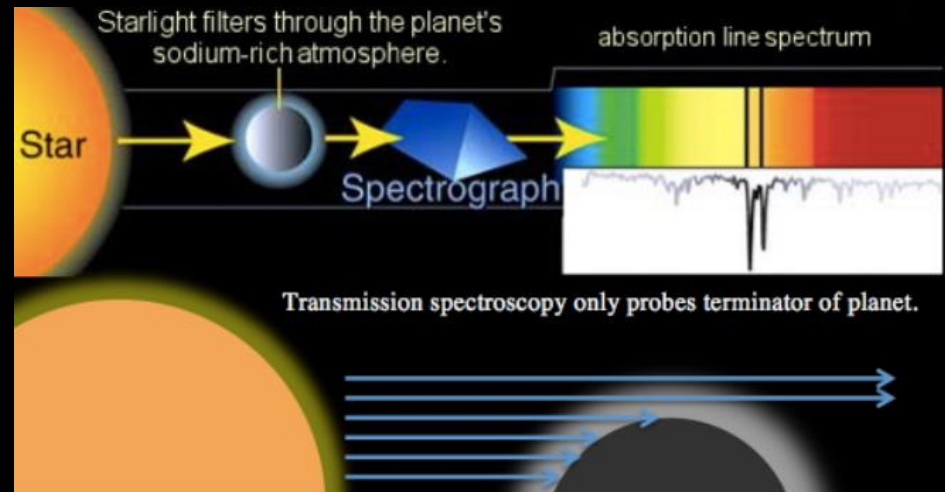
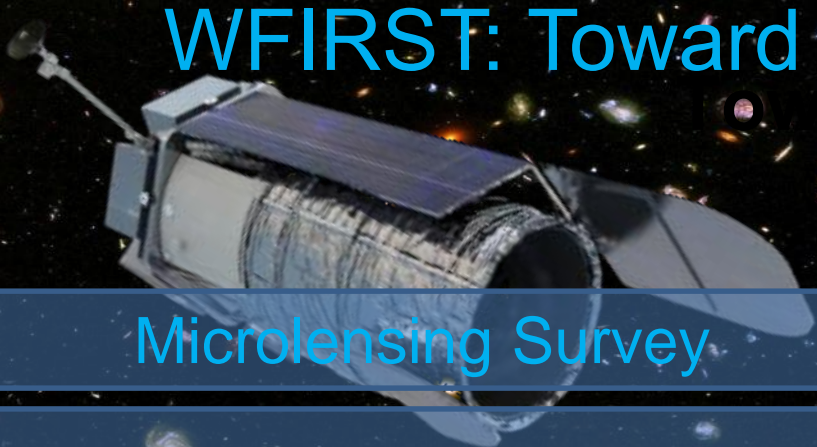


Image credit: A. Field, STScI /Batalha PSU

WFIRST: Toward the “Pale Blue Dot”

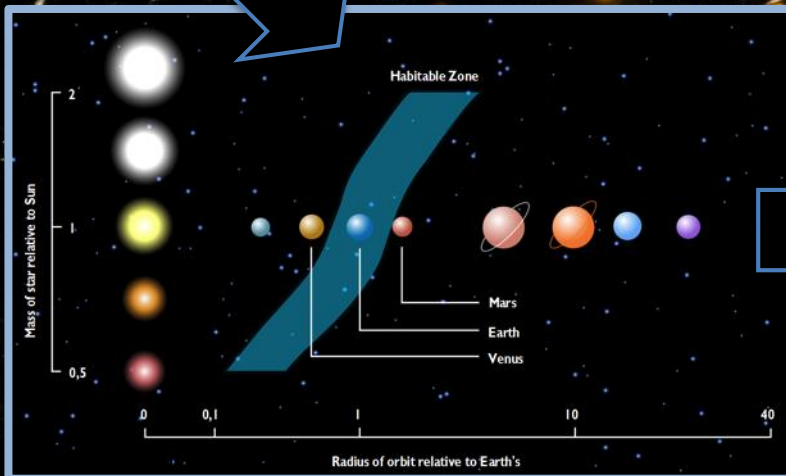


Microlensing Survey

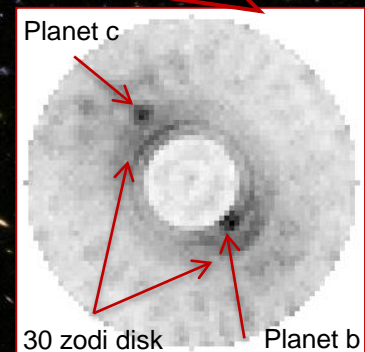
- Inventory the outer parts of planetary systems, potentially the source of the water for habitable planets.
- Quantify the frequency of solar systems like our own.
- Confirm and improve Kepler's estimate of the frequency of potentially habitable planets.
- When combined with Kepler, provide statistical constraints on the densities and heavy atmospheres of potentially habitable planets.

High Contrast Imaging

- Develop crucial technologies for a future mission, and provide practical demonstration of these technologies in flight.
- Provide the first direct images of planets around our nearest neighbors similar to our own giant planets.
- Provide important insights about the physics of planetary atmospheres through comparative planetology.
- Assay the population of massive debris disks that will serve as sources of noise and confusion for a flagship mission.



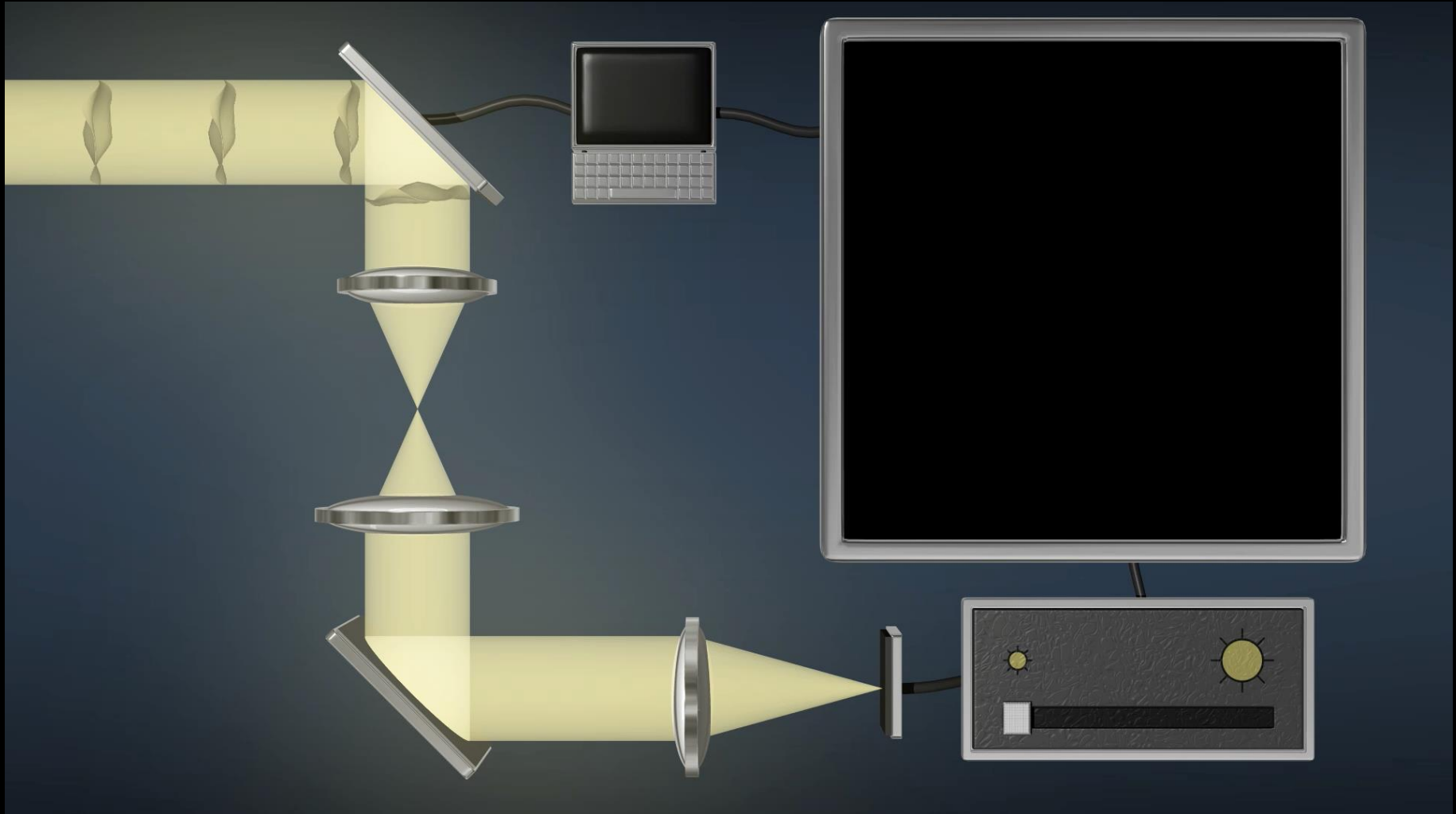
Science and technology foundation for the New Worlds Mission.



Simulated WFIRST coronagraph image of the 47 UMa planetary system

Internal Coronagraph

Controls Diffraction to Reveal Exoplanets in “Dark Hole”



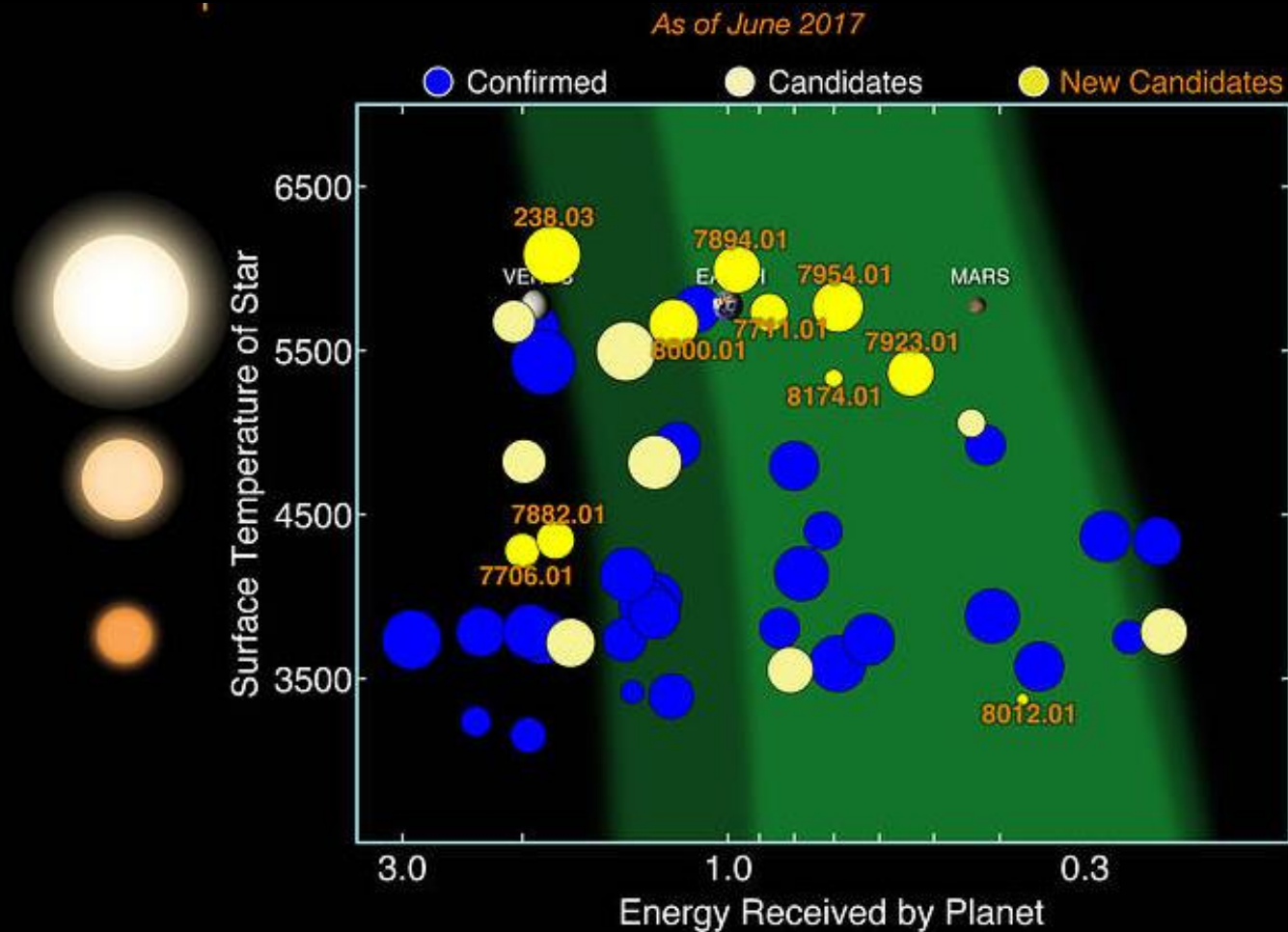
A Familiar Habitable Zone



Credit: Luc Forsyth

Kepler Habitable Zone Planets

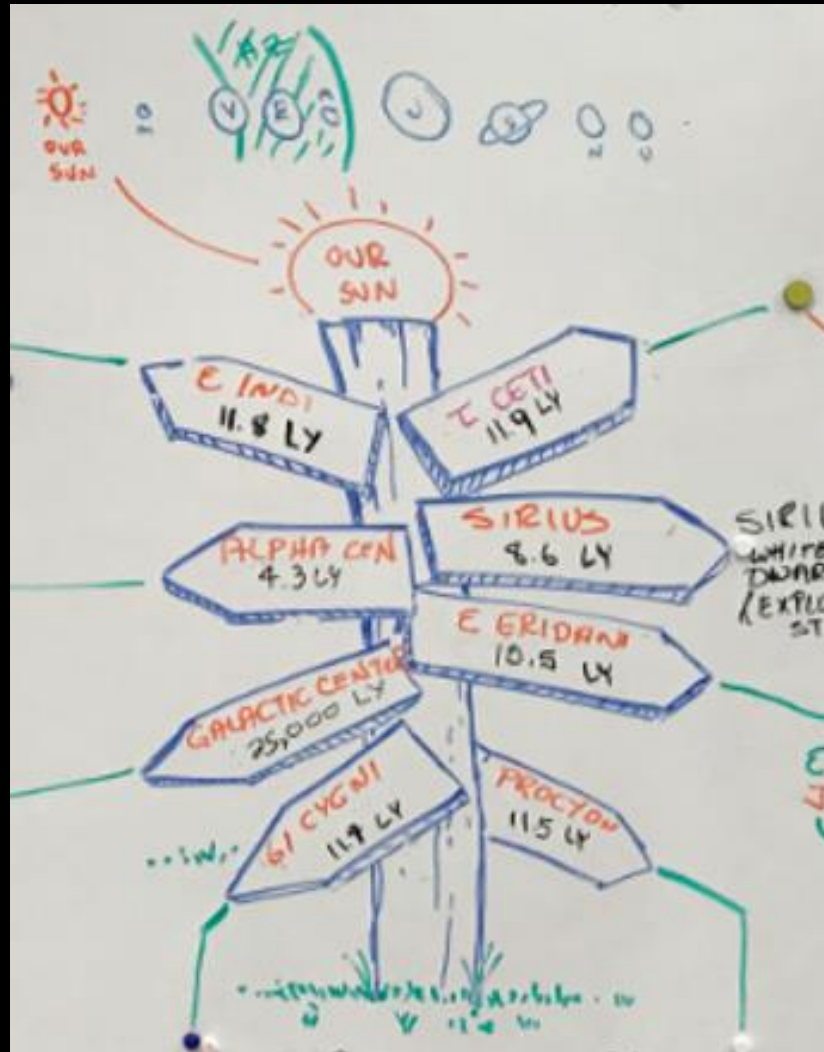
As of June 2017



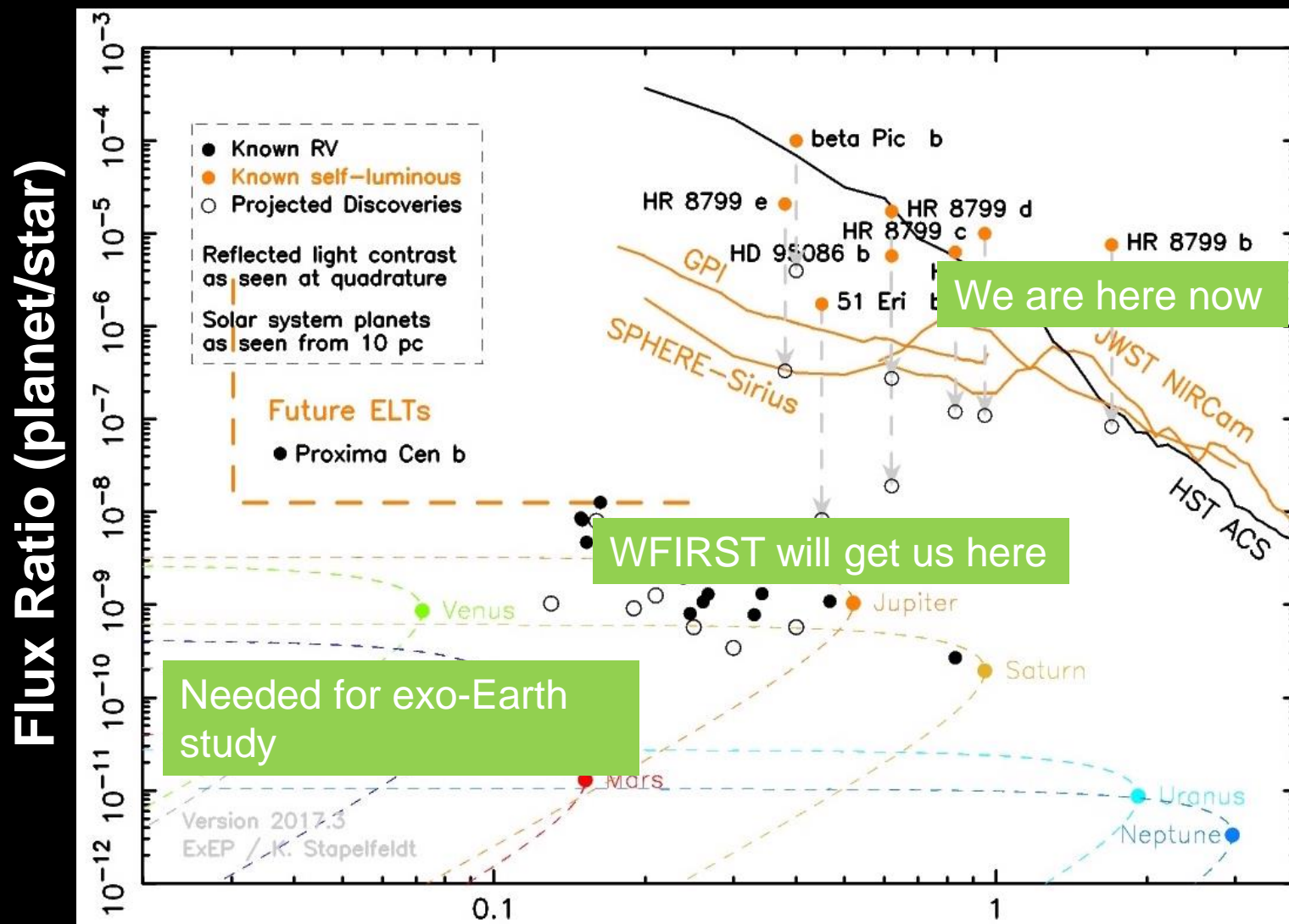
Credit: NASA/Ames Research Center/W. Stenzel

Exploring our Nearest Neighbors

For Earth-like planets



Challenge to Directly Image Exo-Earths



Angular Separation (between planet and star, arcsec)

“Blue of the sky”

measures
total amount
of atmosphere

**“Vegetation
jump”**

indicates
presence of
land plants

Carbon dioxide
suggests possible
volcanic activity

Methane
indicates
presence of
anaerobic
bacteria

**Oxygen
and ozone**
were produced
by living organisms

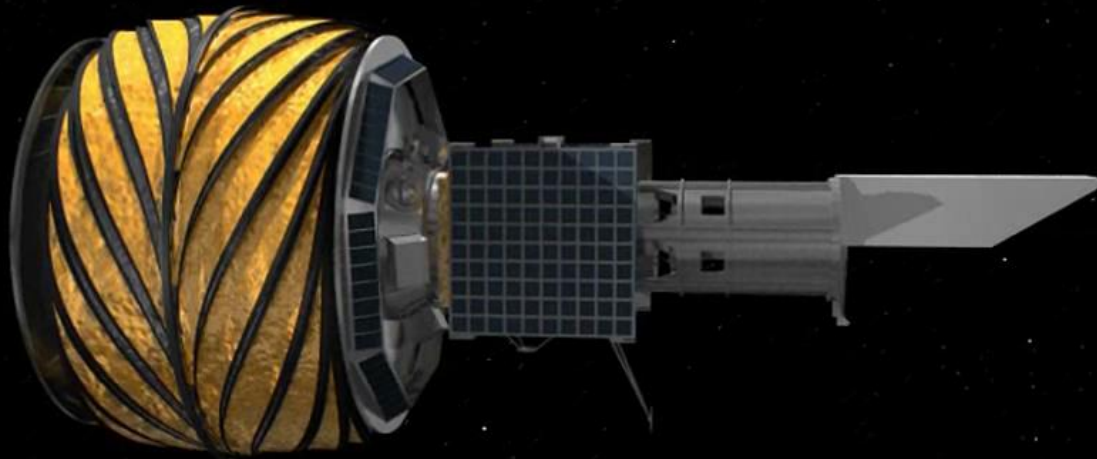
**Water
vapor**
suggests
habitability

Credit: M. Turnbull



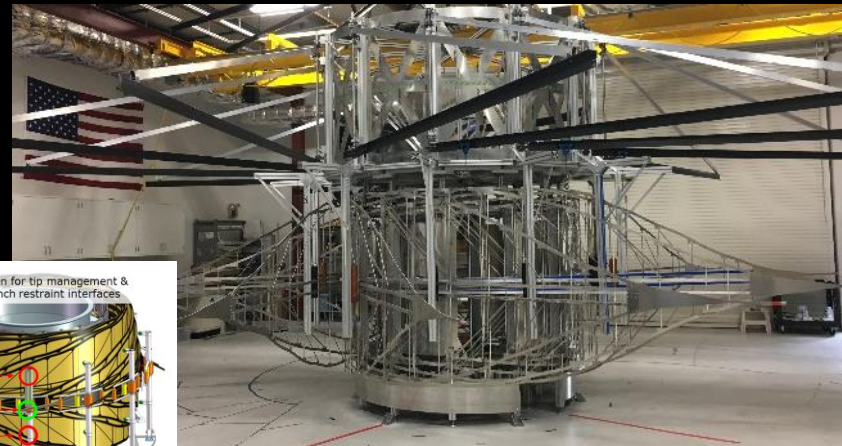
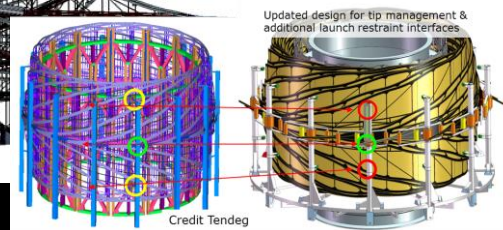
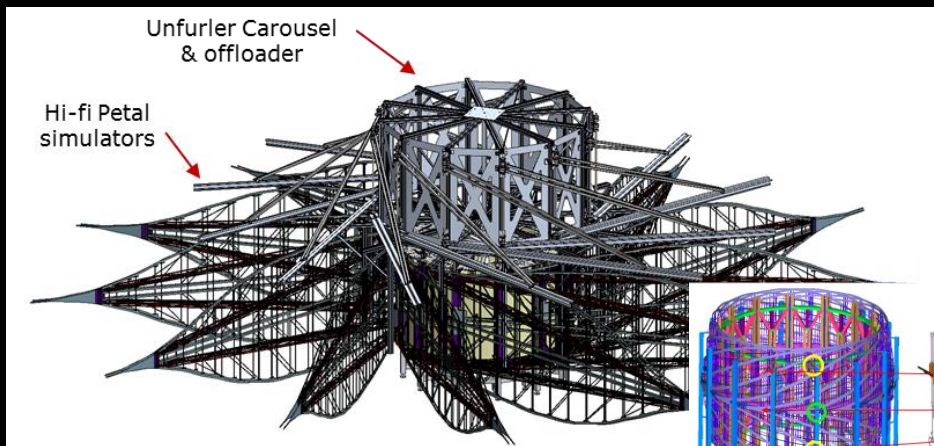
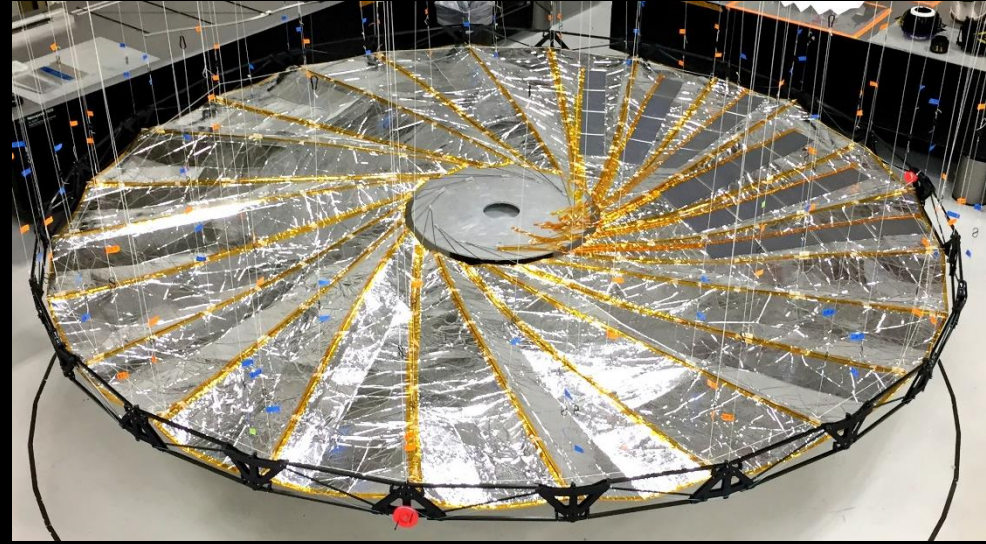
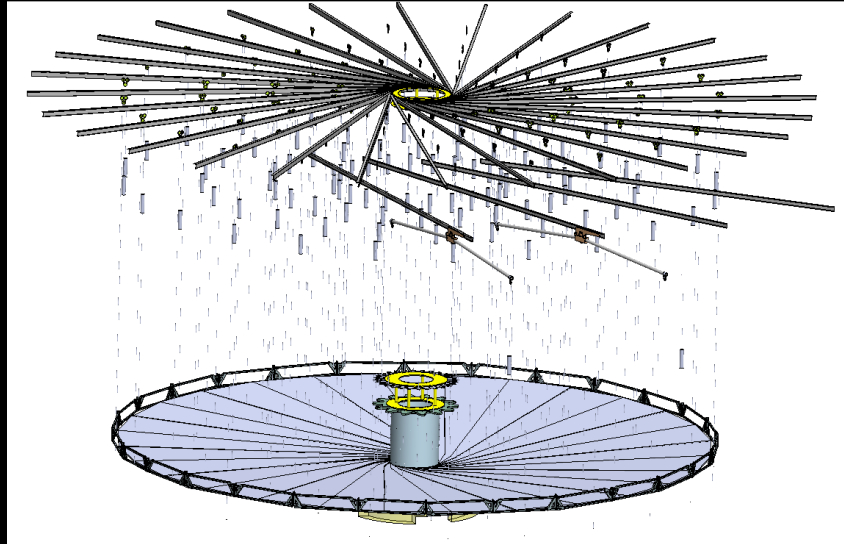
Starshade (External Occulter)

Blocks Starlight, Controls Diffraction prior to Entering Telescope

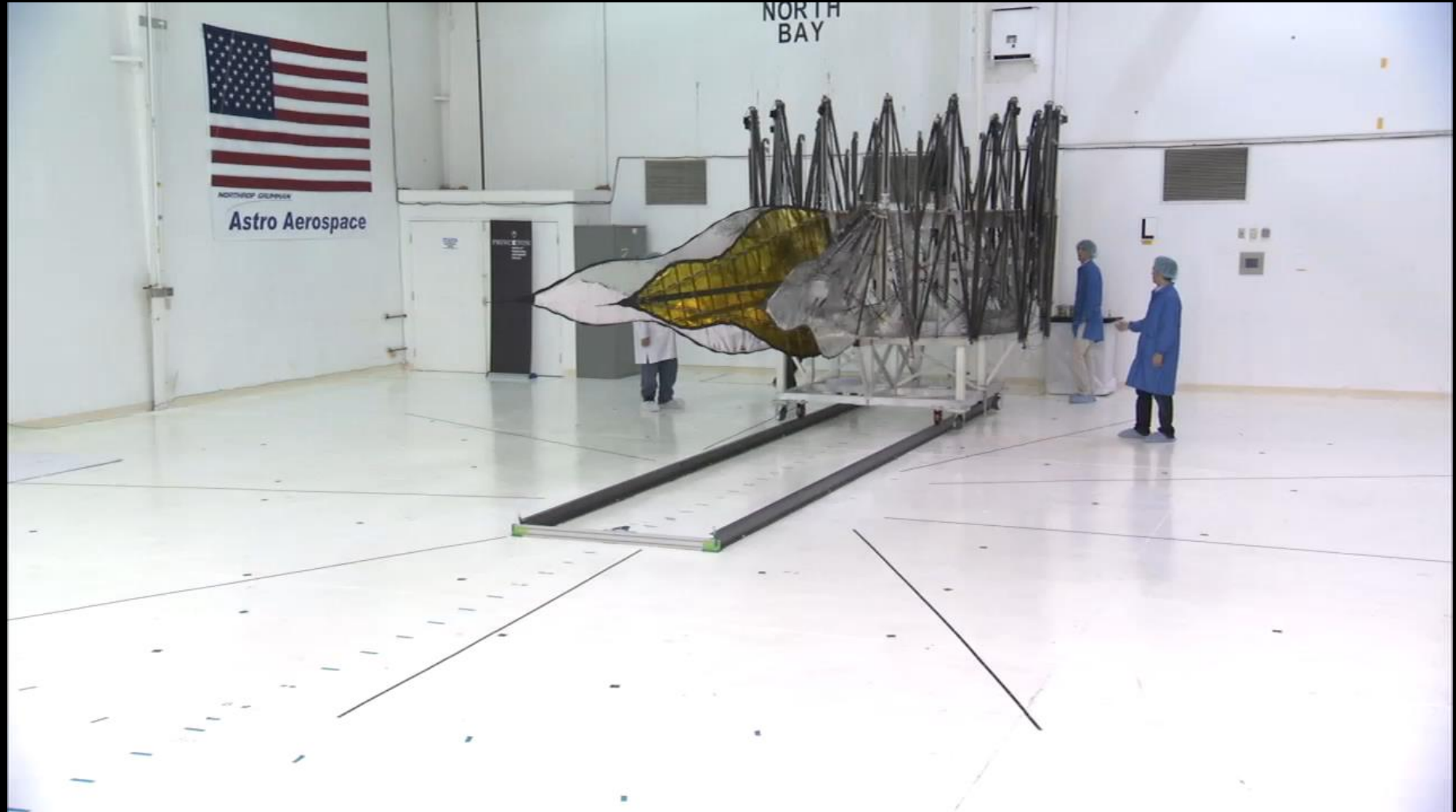


Credit: NASA/JPL

Roccor / Tendeg: gravity offloading of origami optical shield and petal deployment testbed



Petal Deployment at NGAS Asto Aerospace (Goleta, Ca)



Early Inner Disk Deployment Trials at JPL

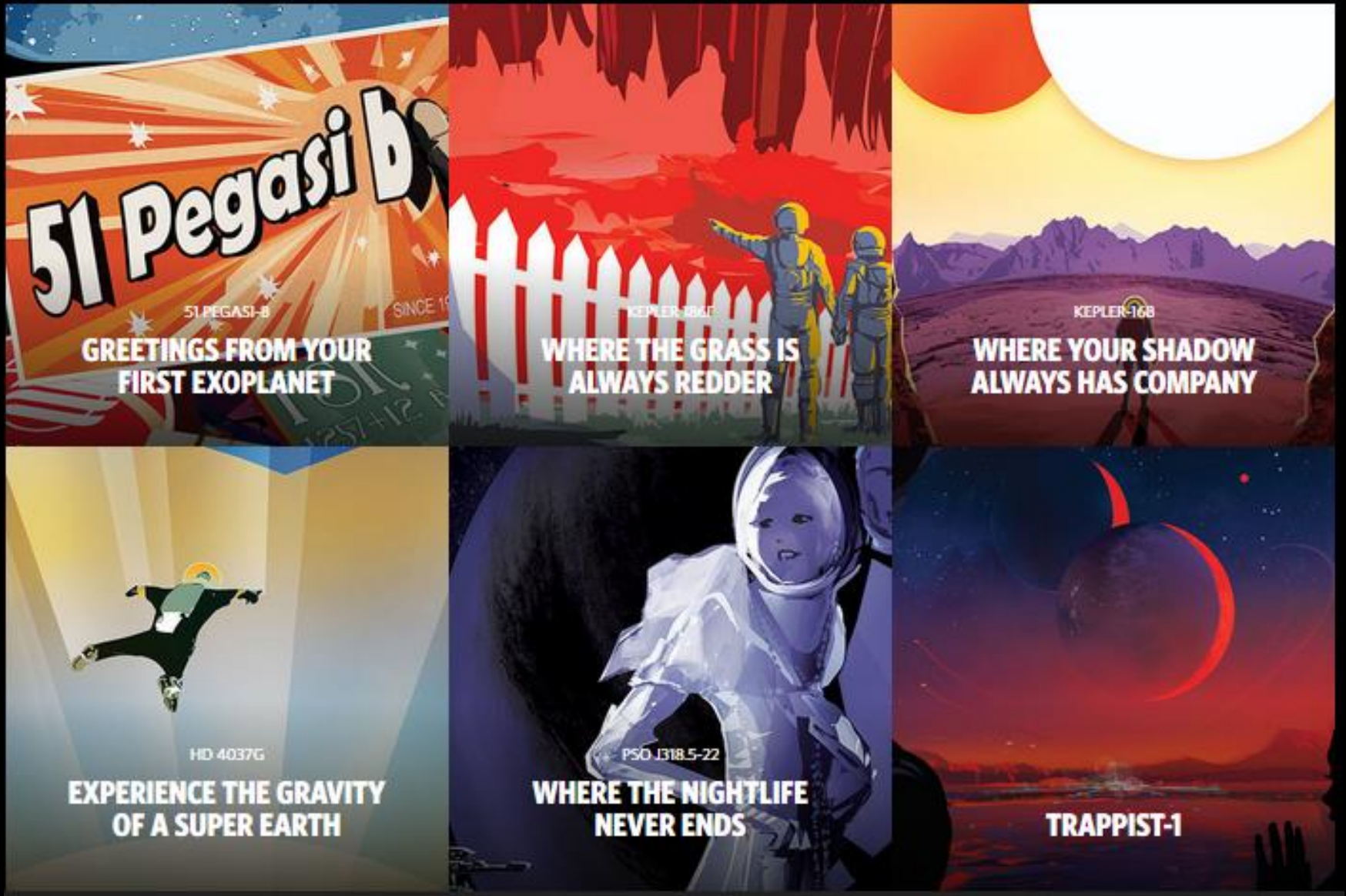


Credit: NASA/JPL

petal deployment testbed



Exoplanet Travel Bureau





Jet Propulsion Laboratory
California Institute of Technology

jpl.nasa.gov

Fun with Exoplanet Travel Bureau

Communicating Exoplanets to Citizens of our own World



For any World we will ever Explore, an Artist and a Poet will have been there First

“EXOPLANET EARTH” EDITION OF TRAPPIST-1

Connecting exoplanet Science Enthusiasm to our own World



Our Star appears as a Leo Sun as seen from Trappist-1

ARIEL

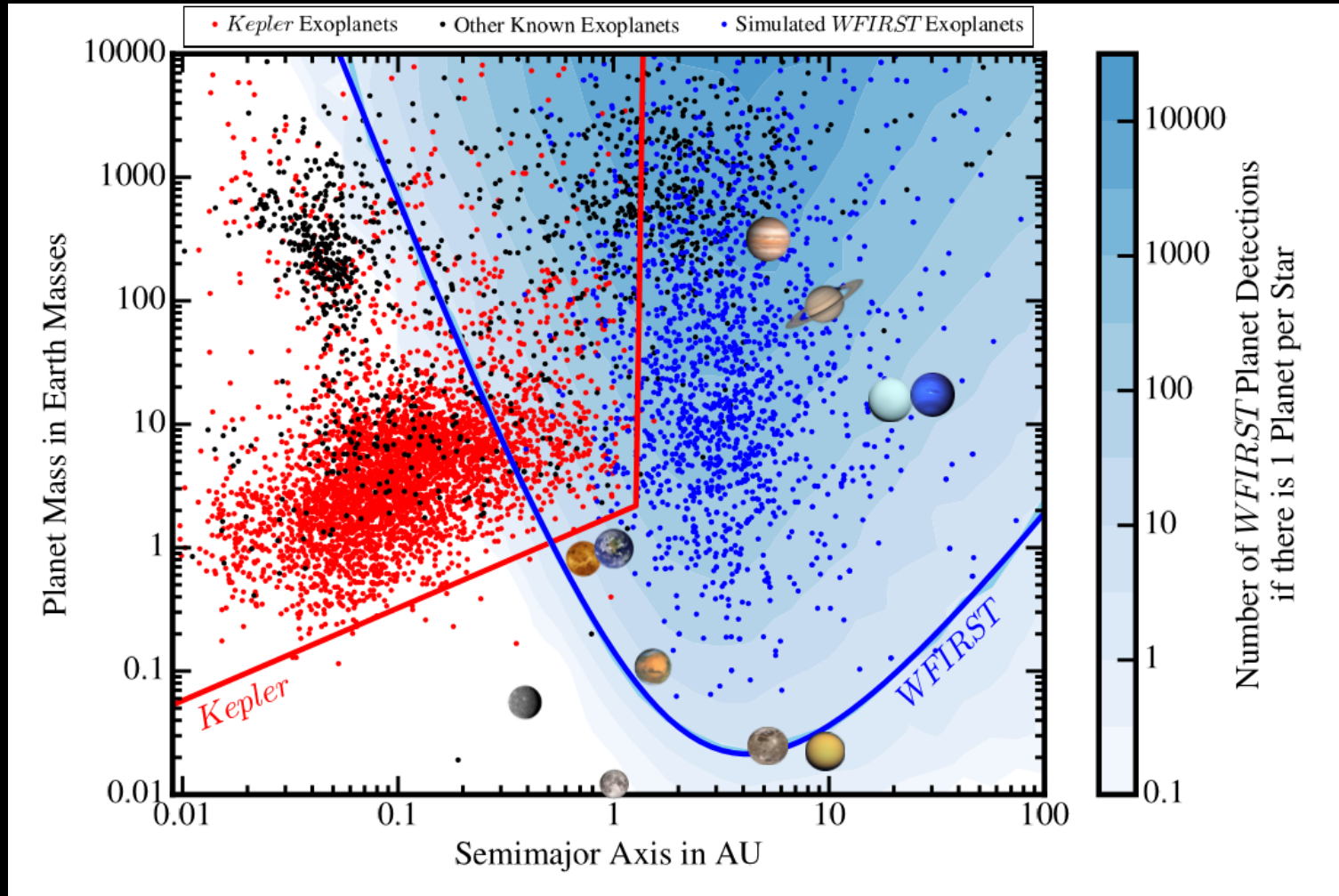
Near- and mid-IR transit spectroscopy

- ESA approved ARIEL as M4 science mission and 2028 launch.
- ARIEL will conduct near- and mid-IR transit spectroscopy of hundreds of planets Neptune-sized and larger.
- ARIEL is led by G. Tinetti of Univ. College London



WFIRST Microlensing

Completing the Census Begun by Kepler



NASA Exoplanet Exploration Program

Astrophysics Division, Science Mission Directorate

Changes since last ExoPAG

